



# Visual letter similarity effects during sentence reading: Evidence from the boundary technique

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## ABSTRACT

The study of how the cognitive system encodes letter identities from the visual input has received much attention in models of visual word recognition but it has typically been overlooked in models of eye movement control in reading. Here we examined how visual letter similarity affects early word processing during reading using Rayner's (1975) boundary change technique in which the parafoveal preview of the target word was either identical (e.g., *frito-frito* [fried]) or a one-letter-different nonword (e.g., *frjto-frito* vs. *frgto-frito*). Critically, the substituted letter in the nonword was visually similar (based on letter confusability norms) or visually dissimilar. Results showed shorter viewing times on the target word when the parafoveal preview was visually similar than when it was visually dissimilar. Thus, visual letter similarity modulates the integration of parafoveal and foveal information during sentence reading. Future implementations of models of eye movement control in reading should incorporate a more developed orthographic-lexical module to capture these effects.

## 1. Introduction

When reading, adults show a remarkable ability to access the appropriate lexical entry among thousands of potential competitors—some of them perceptually similar (e.g., compare *moose* vs. *mouse* or *calm* vs. *clam*)—in 150–300 ms (see Rayner, Pollatsek, Ashby, & Clifton, 2012, for review). This process requires a set of highly efficient operations that extract the identity and the order of the letters that compose each word (Grainger, 2018). In hierarchical models of letter/word recognition (e.g., see Dehaene, Cohen, Sigman, & Vinckier, 2005; Grainger, Rey, & Dufau, 2008, for neural models), the visual features of the letters are combined by shape-specific letter detectors (e.g., “a” and “A”, but not “A”, activate the shape-specific letter detector of the letter “a”). These letter detectors are in turn, combined by complex, case-insensitive letter detectors (e.g., “a”, “A”, and “A” would activate the complex letter detector of “a”), which, in turn, drive the process of lexical access. Although a detailed account of the orthographic processes that underlie lexical access is necessary for a full comprehensive model of eye movement control during reading (Reichle, 2015), the most influential models of eye movement control in reading (e.g., E-Z Reader model, Reichle, Pollatsek, Fisher, & Rayner, 1998; SWIFT model, Engbert, Nuthmann, Richter, & Kliegl, 2005) have not yet implemented detailed modules of orthographic and lexical processing.

Prior research using word recognition tasks (e.g., lexical decision,

naming, semantic categorization) has consistently shown that orthographic processing (i.e., letter identity and letter order) is subject to perceptual uncertainty in the early moments of lexical access (e.g., the pseudoword *nevtral* would generate a similar perceptual input as the word *neutral*), which is eventually resolved (see Marcet & Perea, 2018, for review). Using Forster and Davis' (1984) masked priming technique, words with visually similar embedded letter-like digits (e.g., *M473R14L*) are more effective at activating their base words (*MATERIAL*) than visually dissimilar controls (e.g., *M629R32L*) (Perea, Duñabeitia, & Carreiras, 2008). That is, the digit 4 in *M473R14L* activates the letter detector corresponding to the visually similar letter A. Furthermore, Marcet and Perea (2017) found that word response times to a target word (e.g., *NEUTRAL*) were faster when the one-letter different prime was visually similar (*nevtral*) than when it was visually dissimilar (*neztral*)—word identification times to *nevtral-NEUTRAL* were only slightly longer than those to *neutral-NEUTRAL* (see also Marcet & Perea, 2018, for evidence with multi-letter homographs [e.g., *docurment-DOCUMENT* faster than *docusnent-DOCUMENT*]). Taken together, these findings favor the view that in the initial moments of word processing, there is some uncertainty concerning letter identity for highly visually similar letters (e.g., *nevtral* produces a similar perceptual input as *neutral*). In order to shed more light on the time course of the effects of visual letter similarity during word recognition, Gutiérrez-Sigut, Perea, and Marcet (2018) conducted two masked priming

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experiments while measuring event-related potentials—they used the same materials as Marcet and Perea (2017). Gutiérrez-Sigut et al. found that, at an early time-window associated with orthographic processing (N250; see Grainger & Holcomb, 2009, for review), the ERP waves for the identity condition (e.g., *neutral-NEUTRAL*) and the visually similar condition (*nevtral-NEUTRAL*) behaved similarly, while the visually dissimilar condition (*neztral-NEUTRAL*) produced a larger negativity. This is consistent with the idea of an early perceptual uncertainty concerning letter identity for visually similar letters. In addition, at a later time-window associated to lexico-semantic component (N400), the visually similar condition (*nevtral-NEUTRAL*) produced a larger negativity than the identity condition. This latter finding suggests that the uncertainty concerning letter identity is resolved over time.

The issue under scrutiny in the current experiment is whether these visual letter similarity effects that have been found in word identification tasks with the masked priming technique can be generalized to normal reading. When we read text, we extract information not only from the fixated word, but also from the following word/s in the parafovea (see Rayner et al., 2012, for review). Importantly, information in the parafovea has shown to impact the processing of the word once it is fixated in the fovea, hence this allows for an ecological scenario to examine visual letter similarity effects during the early stages of word processing. An excellent technique to tap these early word identification processes during text reading is Rayner's (1975) gaze-contingent boundary change paradigm. Rayner's boundary change technique allows for the manipulation of parafoveal information that is available to the reader before the foveal processing of a target word (see Fig. 1 for a depiction of the technique). Importantly, although the text may be altered, readers are typically unaware of these changes. Similarly to the masked priming technique, the boundary technique examines the relationship between a prime stimulus and a target stimulus (e.g., the parafoveal previews *nevtral* or *neztral* and the target word *neutral*). Results from this paradigm have revealed that the nature of the codes integrated across fixations is orthographic (or phonological) rather than visual. As found by McConkie and Zola (1979) and Rayner, McConkie, and Zola (1980), changing the case of words from fixation to fixation (e.g., *cHaIr* → *ChAiR*) does not interfere with reading. Likewise, in a

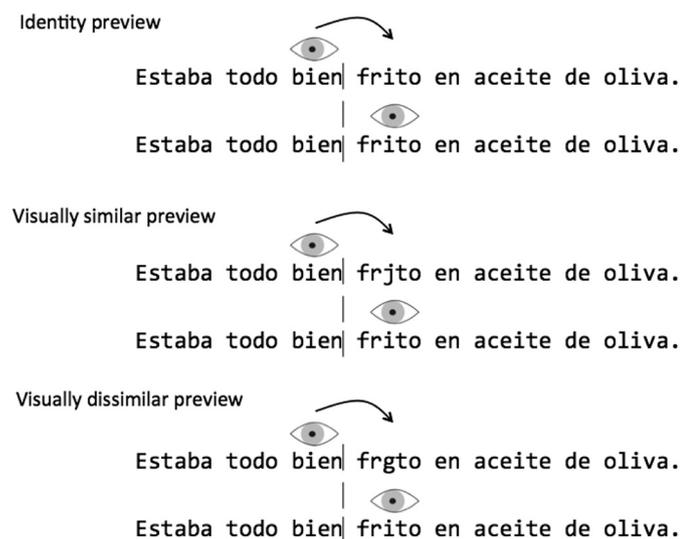


Fig. 1. Description of an eye movement contingent display-change trial with the three experimental conditions (identity preview, visually similar preview, visually dissimilar preview). The eye symbol represents where the reader is fixating, and the arrow represents the saccade crossing the invisible boundary (the dashed vertical line) preceding the target word. Before crossing the boundary, the sentence is presented with the identity, visually similar or dissimilar previews. When the eyes cross the boundary, the parafoveal preview is replaced by the target word.

change detection paradigm, Slattery, Angele, and Rayner (2011) found that the probability of detecting a display change from the parafoveal preview to the target was higher when there was a change in letter identities (*jNxEVa* → *gReEn*) than when there was a change in letter case (*gReEn* → *GrEeN*) (see also Angele, Slattery, & Rayner, 2016, for discussion). Finally, recent research has shown that readers may also extract semantic and higher-order contextual information from the parafoveal previews (e.g., see Hohenstein & Kliegl, 2014, to cite one recent example).

To explain how orthographic information from the parafoveal previews is integrated across saccades in the word recognition stream, Rayner et al. (1978; see also Rayner et al., 2012) proposed the “preliminary letter identification” hypothesis. The rationale of this account is that while the eye is fixating on word  $n$ , factors such as visual acuity and lateral masking would hinder the identification and relative order of the letters in word  $n + 1$ . Hence, orthographic processing in the parafovea would be subject to letter confusability, particularly for those letters that share many visual features (e.g., *b* and *h*). Support for the preliminary letter identification hypothesis comes from the boundary experiments reported by Rayner and colleagues (Rayner, 1975; Rayner et al., 1978; Rayner, Well, Pollatsek, & Bertera, 1982). In a sentence reading experiment, Rayner (1975) included an identity preview (e.g., *tested*), a visually similar nonword preview (e.g., *trted*) and a visually dissimilar nonword preview (e.g., *tfmed*). Rayner (1975) found shorter viewing times for the target words when the preview was a visually similar nonword than when the preview was a visually dissimilar preview—this was accompanied by briefer viewing times in the identity condition than in the visually similar preview condition. In the Rayner et al. (1978) experiments, readers looked at a dot in the center of the screen while a word or nonword appeared in the parafovea. When the participants moved their eyes toward the letter string, the word/nonword was replaced by a target word that the participant had to read aloud. The parafoveal preview conditions comprised: 1) a visually similar word (*police-palace*); 2) a visually similar replaced-letter nonword (*pcluce-palace*); and 3) a visually dissimilar replaced-letter nonword (*pyltce-palace*). Rayner et al. (1978) found longer naming times for those words that were preceded by a visually dissimilar preview than by a visually similar preview, which in turn produced longer naming times than the identity preview condition (see also Rayner et al., 1982, for converging evidence). Similarly, other boundary change experiments only found slightly faster viewing times on a target word in the identity condition than in a visually similar preview condition (e.g., *song-song* vs. *sorp-song*) (e.g., Altarriba, Kambe, Pollatsek, & Rayner, 2001; Balota, Pollatsek, & Rayner, 1985; Pollatsek, Rayner, & Balota, 1986; see also Cutter, Drieghe, & Liversedge, 2015, and Hyönä, Bertram, & Pollatsek, 2004, for reviews).<sup>1</sup>

Taken together, the above-cited experiments suggest that visual letter similarity plays a role in the initial moments of processing during normal reading. However, a limitation of these experiments is that visual letter similarity was merely operationalized in terms of letter shape. For instance, when creating the stimuli in the visually similar condition, Rayner et al. (1982) indicated that “every ascender was replaced by an ascender, every descender was replaced by a descender, and letters that did not extend above or below the line of print were replaced by other similar nonascending or nondescending letters” whereas in the visually dissimilar letter condition, “every letter was replaced by a dissimilar letter, with ascenders replaced by descenders or letters that did not extend above or below the line” (p. 542). That is, visual letter similarity was simplified to three categories of letter shape:

<sup>1</sup> Pollatsek, Lesch, Morris, and Rayner (1992) found a sizeable advantage of the identity condition over a visually similar condition (around 25 ms in the first fixation on the target word), but this difference occurred primarily when the visually similar preview did not share the initial letter with the target word (e.g., *aerial-cereal*).

(a) ascending letters (e.g., *b*, *t*, *h*); (b) descending letters (e.g., *g*, *j*, *p*), and (c) neutral (short) letters (e.g., *a*, *v*, *m*). Whereas it is quite frequent that letters that share the basic shape are also visually similar (e.g., *b* and *h*; *c* and *e*), two letters may share the outline letter shape while being visually dissimilar (e.g., *d* and *k*; *r* and *s*) and, conversely, two letters may differ in outline letter shape while being visually similar (e.g., *i* and *j*).

Importantly, letter shape per se does not seem to be the critical factor underlying visual similarity effects in word recognition. An excellent demonstration is the proofreading experiment conducted by Paap, Newsome, and Noel (1984). They found that the percentage of misses did not depend on whether the misspelled word shared the letter shape with the target word, but on the visual confusability of the replaced letter: for the target word *than*, the misspelled items *tdan* [same letter shape] and *tman* [different letter shape] were detected more easily than *than* or *tnan* [note that both *b* and *n* are visually confusable to *h*, but only *b* shared the letter shape with *h*]. Further evidence that letter shape per se does not play a main role in word recognition comes from the lexical decision experiment conducted by Perea and Panadero (2014). They found similar response times for visually similar and visually dissimilar pseudowords created by replacing a letter from a base word with the same/different letter shape (e.g., *fiesda* vs. *fiesna*; the base word was *fiesta*). More recently, in a series of masked priming lexical decision experiments, Marcet and Perea (2017) found faster word identification times for visually similar pairs over visually dissimilar pairs regardless of letter shape (*frjto-FRITO* [*fried*] faster than *frgto-FRITO*; *nevtal-NEUTRAL* faster than *neztal-NEUTRAL*). Taken together, these findings suggest that letter shape per se does not play a major role during foveal word processing.

The lack of an effect from outline letter shape during word identification has also been obtained during sentence reading. Johnson, Perea, and Rayner (2007) included parafoveal previews created by transposing two letters (e.g., *jugde* from the target word *judge*) or by replacing two letters that kept the letter shape (*jupte*—note that *p* was replaced with another descending letter and *t* was replaced with another ascending letter) together with an identity condition (the parafoveal preview *judge*). Johnson et al. (2007) found shorter viewing times on the target word in the transposed-letter condition than in the replacement-letter condition (*jugde-judge* < *jupte-judge*) and, furthermore, viewing times on the target word were only slightly shorter in the identity condition than in the transposed-letter condition (see also Winkler & Perea, 2013, for similar evidence in Thai). Moreover, this pattern of data occurred regardless of whether the parafoveal previews did or did not maintain the same outline letter shape as the target word (e.g., similar advantage for *corwn-crown* vs. *ceswn-crown* as for *cebrk-clerk* vs. *cbork-clerk*). The Johnson et al. (2007) findings have two important implications: 1) there is some uncertainty concerning letter order when processing parafoveal stimuli, thus extending the Perea and Lupker (2003) masked priming findings to a normal reading scenario; and 2) readers were able to obtain more information on the identities of the letters from the parafoveal previews over and above letter shape.

The main goal of the current boundary change experiment was to examine the role of visual letter similarity on parafoveal processing during sentence reading while controlling for outline letter shape. The criterion to select the pairs was based on visual letter similarity ratings (see Simpson, Mousikou, Montoya, & Defior, 2012). The preview/target stimuli were extracted from the masked priming experiments conducted by Marcet and Perea (2017) in Spanish. This allows us to directly compare the visual letter similarity effects when using masked priming during visual word recognition and when using parafoveal previews during sentence reading (see Johnson et al., 2007, for a similar strategy of using stimuli from prior masked priming experiments). For the visually similar condition, the target words contained a middle letter with a high degree of similarity with another letter: *i/j* (5.17 out of 7 in the Simpson et al., 2012, ratings) and *u/v* (4.93 out of 7)—note that *i/j* and *u/v* were originally allographs that acquired a different orthography

and phonology in the Middle Ages. In Spanish, the consonant letter *j* corresponds to the voiceless velar fricative /x/ (this may sound like the Scottish grapheme *ch* in *loch*), whereas the consonant letter *v* corresponds to the voiced bilabial stop /b/. This manipulation allowed us to generate parafoveal previews created by replacing a single letter that could be visually similar (e.g., *frjto*; the target word was *frito* [*fried*]) or visually dissimilar (*frgto*)—note that we kept the ascending/descending pattern in the visually dissimilar condition.

The present experiment has two advantages over previous studies on visual letter similarity during sentence reading. First, as letter shape in terms of ascenders and descenders is not a strict marker of visual letter similarity (e.g., the letters *k* and *d* are not visually very similar despite sharing the letter shape, whereas *i* and *j* are visually similar despite not sharing the letter shape), we used a criterion of visual letter similarity based on a letter confusability matrix (i.e., the matrix collected by Simpson et al., 2012). Second, we controlled the consonant/vowel status of the replaced letters across visually similar and visually dissimilar previews (e.g., *frjto* vs. *frgto*), as this factor may modulate lexical access such as (see New, Araujo, & Nazzi, 2008; Perea, Marcet, & Acha, 2018, for evidence during word recognition). Consonant/vowel status was not controlled in previous research (e.g., the visually similar preview *pcluce* was compared with the visually dissimilar *pyltce* for the target word *palace*; see Rayner, 1975; Rayner et al., 1978)—in fairness to Rayner and colleagues, the effects of consonant/vowel status of letters during word recognition only started to be studied in the past two decades.

In sum, we used Rayner's (1975) boundary change technique to examine the role of visual letter similarity during sentence reading while controlling for outline letter shape. We employed three parafoveal preview conditions: (a) a parafoveal preview that was identical to the target word (identity preview; e.g., *frito-frito* [*fried*]); (b) a parafoveal preview in which an internal letter from the target word was replaced by a letter that was visually similar (visually similar preview; e.g., *frjto-frito*); and (c) a parafoveal preview in which an internal letter from the target word—the same as in the visually similar condition—was replaced by a visually different letter (visually dissimilar preview: e.g., *frgto-frito*). The predictions are clear-cut. According to the preliminary letter identification hypothesis (Rayner et al., 1980, 2012), while fixating on word *n*, readers would obtain information from the letters of word *n + 1* in the parafovea. As Rayner et al. (2012) claimed, “information based partly on visual features and partly on orthographic rules would begin accumulating for the beginning letters of the parafoveal word, but identification would not take place until after the eye movement” (p. 123). Therefore, the preliminary letter identification hypothesis would predict that a visually similar nonword preview (*frjto*) would produce a processing advantage on the subsequent word (i.e., shorter viewing times) over a visually dissimilar nonword preview (*frgto*). This outcome would generalize the idea that there is some degree of uncertainty on the identity of the letters during word recognition not only in foveal processing (see Marcet & Perea, 2017, in press, for evidence with masked priming) but also in parafoveal processing. Alternatively, if—unlike foveal processing—the processing of orthographic information in the parafovea occurs mostly in terms of low-spatial frequency information that is insensitive to fine-grained processing, one would expect similar viewing times on the target words when preceded by a visually similar (*frjto-frito*) or visually dissimilar parafoveal preview (*frgto-frito*). This latter outcome would reveal a dissociation between orthographic processing in the fovea and parafovea.

## 2. Method

### 2.1. Participants

The participants were twenty-seven undergraduate students from the Universitat de València. All of them were native speakers of Spanish

with normal vision—none of them used glasses or contact lenses. This study was approved by Experimental Research Ethics Committee of the Universitat de València and written informed consent was obtained from all participants before starting the experimental session. Sample size ( $N = 27$ ) was the same as in previous experiments on visual letter similarly with the masked priming technique (see Marcet & Perea, 2017).

## 2.2. Apparatus

To register the participant's eye movements during sentence reading, we employed an Eyelink 1000 video-based eye tracker with a 1000-Hz sample rate,  $< 0.5^\circ$  average gaze position error, and a 3 ms delay—this device only recorded the eye movements from the right eye. The sentences were presented in a 24-inch LCD Asus VG248 monitor with a refresh rate of 144 Hz.

## 2.3. Materials

We created 240 sentences in Spanish. Each sentence contained a target word with  $i/j$  or  $u/v$  as internal letters (e.g., the target word *frito* [fried] in the sentence “Estaba todo bien frito en aceite de oliva.” [It was all well fried in olive oil.]). These target words were extracted from the materials used by Marcet and Perea (2017) in their masked priming experiments. The mean Zipf frequency was 4.02 (range: 1.94–5.87), the mean number of letters was 6.7 (range: 5–8), and the mean OLD20 was 2.0 (range: 1.3–3.3) in the Spanish lexical database (Duchon, Perea, Sebastián-Gallés, Martí, & Carreiras, 2013). For each target word, we created three parafoveal previews: 1) the same as the target word (identity condition; e.g., preview: *frito*; target: *frito*); 2) a nonword that was the same to the target word except for the replacement of a letter with a visually similar letter ( $i \rightarrow j$ ,  $j \rightarrow i$ ,  $u \rightarrow v$ ,  $v \rightarrow u$ ) (visually similar condition: e.g., preview: *frjto*; target: *frito*); 3) a nonword was the same as the target word except for the replacement of a letter—the same as in the previous condition—with a visually dissimilar letter with the same letter shape as in the visually similar condition (visually dissimilar condition: e.g., preview: *frgto*; target: *frito*). The parafoveal previews were counterbalanced across three lists following a Latin square design. Each participant received 80 trials in each of the three conditions. The complete set of sentences, including the parafoveal previews, is presented in the Appendix. To prevent the target words from being anticipated in the previous context, the sentences included target words that were not easily predictable. This was verified via a cloze task in which the initial part of each sentence—until the word preceding the target word—was presented to 10 naïve individuals that were asked to predict the following word—none of these individuals took part in the experiment. The percentage of words that was predicted from the previous context was very low ( $< 1\%$ ). We also verified that the sentences were easy to understand: the ten individuals that performed the cloze task were also asked to rate how comprehensible each sentence was (1 = not understandable at all; 10 = very easily understandable). The average score was very high ( $M = 9.9$ ).

## 2.4. Procedure

The experimental session took place in a dimly lit room. The sentences were presented in 20-pt Consolas font (i.e., a fixed-width font) using the software from the University of Massachusetts Eyetracking laboratory (Eyetrack; <https://blogs.umass.edu/eyelab/software/>) in a Windows XP computer. The participants were sitting approximately 60 cm from the computer monitor. At that distance, the 20-pt Consolas font yielded approximately 2.53 letters per degree of visual angle. The participants were first informed about the experimental procedure. Their task was to read sentences for comprehension in a computer screen while their eye movements were registered. They were told that there would be comprehension questions on the sentence they had just

read in around 20% of the time. They were also told that before starting the experiment, the system had to be calibrated—this process could be repeated along the experiment. In order for the participants to be comfortable and to reduce head movements, we used a chinrest and a height adjustable chair.

The experiment procedure began with a three-point calibration phase in which the participants had to look at individual dots on the screen. This was followed by eight practice sentences to familiarize the participants with the procedure. Each trial had the following arrangement. First, a fixation point was presented in the center of the screen to verify the quality of the calibration—the eye-movement device was recalibrated when necessary. Second, a black square was presented on the left side of the screen—this coincided with the location of the initial letter of each sentence. Third, the sentence was presented once the participant looked at the black square. The display change occurred when the participant's eyes crossed an invisible boundary located just before the target word (see Fig. 1). The sentence remained on the screen until the participant finished reading it—participants were asked to press a key on a gamepad. Fourth, on 20% of the trials there was a yes/no comprehension question on the previous sentence—this was done to verify that participants were reading for comprehension. Participants did not notice any displays changes—or in a minuscule number of sentences (no more than five)—when asked after the experiment. Each participant received the sentences in a different random order.

## 2.5. Data analysis

The essential idea underlying Rayner's (1975) boundary technique is that the parafoveal preview allows some preprocessing of the target word. Specifically, if the reader extracts more useful information from the visually similar parafoveal preview than for the visually dissimilar parafoveal preview, the processing time on the target word will be reduced when directly fixated, thus resulting in shorter fixation durations (see Rayner et al., 2012). We examined three eye fixation measures on the target word (i.e., the critical region): 1) the duration of the initial fixation on the target word (first fixation duration); 2) the sum of fixation durations before leaving it (gaze duration); and 3) the duration of the fixation when there was only one fixation (single fixation). Although the key comparison was between the eye fixation durations on the target word in the visually similar vs. the visually dissimilar conditions, we also examined how effective the visually similar condition was relative to the identity condition.

## 3. Results

Participants were quite accurate to responding the comprehension questions (mean accuracy: 94.4%, range: 85–98%). To analyze the eye movement data we employed the suite of programs available at the University of Massachusetts Eyetracking lab (Eyedoctor and Eyedry; <https://blogs.umass.edu/eyelab/software/>). The data were initially screened (e.g., track losses, blinks, early/late display changes) with the EyeDoctor software—this resulted in  $< 7\%$  of the data lost in the target region—and successive fixations within the range of one character were merged as a single fixation. Then the data were processed with Eyedry software. Fixations shorter than 100 ms or longer than 800 ms were removed. Eyedry was also used to obtain the fixation durations on the target word (i.e., the critical region) for the three dependent variables (first fixation duration, single fixation, gaze duration). Before conducting the statistical analyses, and to minimize the influence of outliers, those eye fixation durations that exceeded three standard deviations of the average per subject and condition were removed ( $< 1\%$  of the data). The average eye fixation measures per condition across participants are presented in Table 1.

We analyzed the eye fixation data with linear mixed effects models that included preview-target relationship as a fixed factor and subjects and items as random factors—both intercepts and slopes—using the

**Table 1**

Averages of the eye movement measures (first fixation duration, single fixation duration, and gaze duration) in milliseconds for three preview conditions. Standard Errors are presented between brackets.

	First-fixation duration	Single fixation	Gaze duration
Type of parafoveal preview			
Identity	236 (7)	241 (8)	277 (14)
Visually similar	243 (8)	252 (11)	284 (13)
Visually dissimilar	248 (9)	255 (11)	291 (14)

*lmer* package in R (Bates, Mächler, Bolker, & Walker, 2015). Fixation durations were inverse-transformed (i.e.,  $-1000/\text{fix\_duration}$ ) to maintain the normality assumption of these models—this was the same transformation as in the parallel masked priming experiments conducted by Marcet and Perea (2017). The critical contrast involved the comparison between the visually similar condition and the visually dissimilar condition, but we also compared the identity condition vs. visually similar condition (see Marcet & Perea, 2017, in press). The  $p$  values for each contrast were obtained from the *lmerTest* package (Kuznetsova, Brockhoff, & Christensen, 2017). We employed the maximal random structure model with the first fixation durations:  $\text{LME\_FIXDUR} = \text{lmer}(-1000/\text{FixDur}) \sim \text{previewtype} + (\text{previewtype} + 1|\text{item}) + (\text{previewtype} + 1|\text{subject})$ ,  $\text{data} = \text{VIS\_SIM}$ ). For single fixation duration and gaze duration, we kept that most complex random structure model that successfully converged:  $\text{LME\_GD} = \text{lmer}(-1000/\text{GD}) \sim \text{previewtype} + (1|\text{item}) + (\text{previewtype} + 1|\text{subject})$ .

### 3.1. First fixation duration

The first fixation duration on the target word was longer in the visually dissimilar condition than in the visually similar condition,  $b = 0.091$ ,  $SE = 0.043$ ,  $t = 2.09$ ,  $p = .039$ , and in turn, the first fixation duration on the target word was longer in the visual similar condition than in the identity condition,  $b = 0.110$ ,  $SE = 0.044$ ,  $t = 2.46$ ,  $p = .021$ .

### 3.2. Single fixation duration

Ten advantage of the visually similar condition over the visually dissimilar condition approached significance,  $b = 0.076$ ,  $SE = 0.041$ ,  $t = 1.82$ ,  $p = .077$ , whereas the advantage of the identity condition over the visually similar condition was quite robust,  $b = 0.18$ ,  $SE = 0.048$ ,  $t = 3.71$ ,  $p = .001$ .

### 3.3. Gaze duration

Gaze durations on the target word were longer in the visually dissimilar condition than in the visually similar condition,  $b = 0.103$ ,  $SE = 0.042$ ,  $t = 2.54$ ,  $p = .013$ , and gaze durations on the target words in the visually similar condition were longer than in the identity condition,  $b = 0.113$ ,  $SE = 0.050$ ,  $t = 2.79$ ,  $p = .032$ .<sup>2</sup>

To corroborate the previous analyses and to shed more light on the nature of the effect of visual letter similarity during parafoveal processing, we conducted distributional analyses—via averaging the 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 quantiles per participant and condition—on the first fixation durations, single fixations, and gaze

<sup>2</sup> For the interested readers, the pattern of significant effects was the same if we had applied a logarithm transformation. For the critical comparison (visually similar vs. visually dissimilar), we found  $t = 2.07$ ,  $p = .04$  for first-fixation duration and  $t = 2.54$ ,  $p = .013$  for gaze duration. Similarly, the by-participant and by-item  $t$ -tests on the untransformed data also showed the same pattern (first-fixation duration:  $t(1,26) = 2.20$ ,  $p = .037$ ,  $t(2,239) = 1.99$ ,  $p = .048$ ; gaze duration:  $t(1,26) = 2.38$ ,  $p = .02$ ,  $t(2,239) = 2.53$ ,  $p = .012$ ).

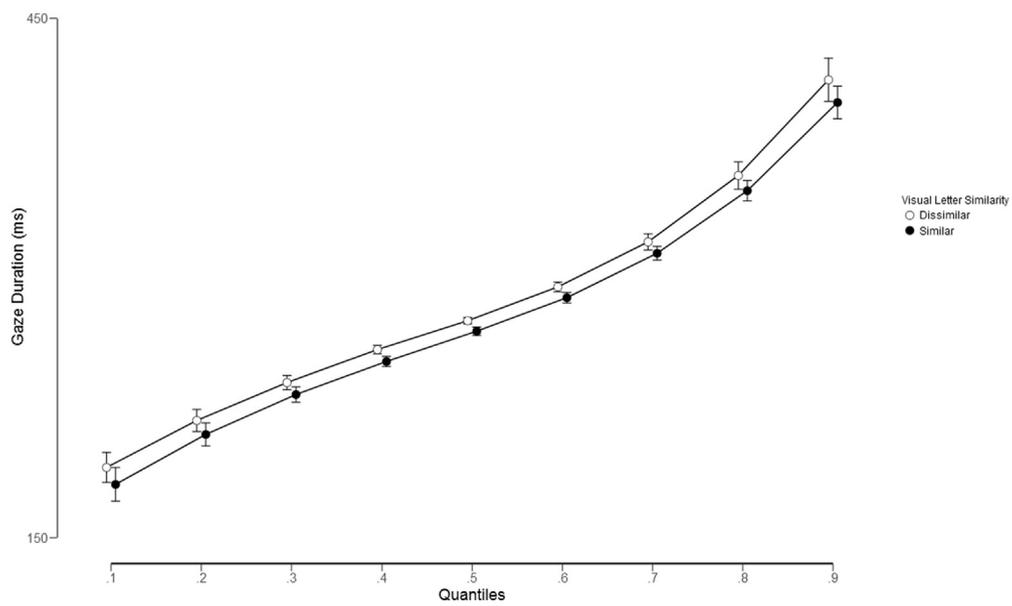
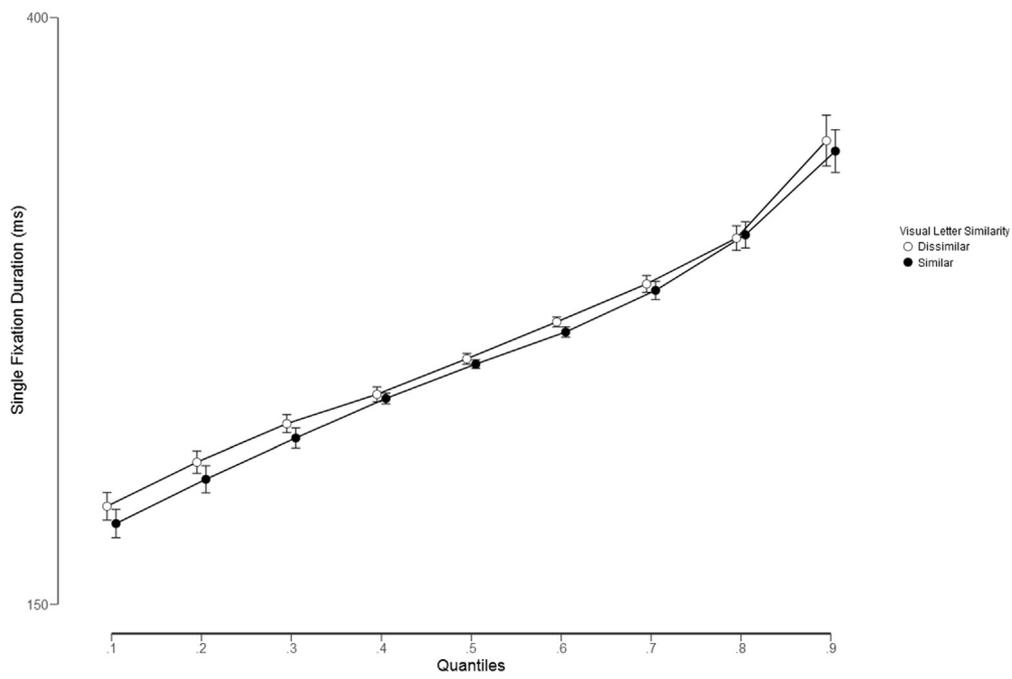
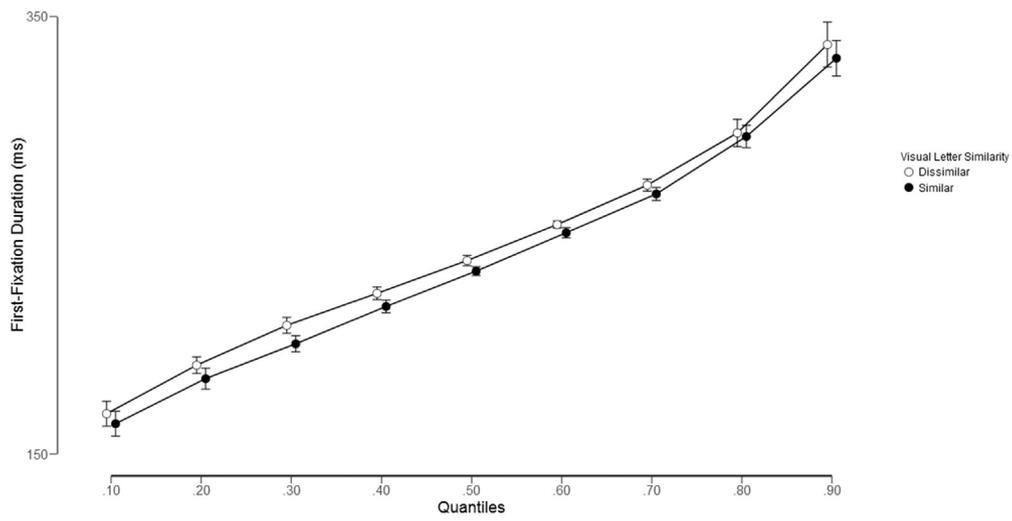
durations. The rationale of these distributional analyses is that they allow us to examine whether the effect is approximately the same magnitude across quantiles (i.e., a shift in the distributions) or whether it grows in the higher quantiles (i.e., a change in shape)—note that this may be used to deduce whether the effect occurs at an encoding or decision stage (e.g., see Gomez & Perea, 2014). The distributional analyses on these three dependent variables are displayed in Fig. 2. As can be seen in the Figure, the preview benefit of the visually similar condition over the visually dissimilar condition was stable across quantiles for first fixation duration and gaze duration (first fixation duration:  $F(1,26) = 5.15$ ,  $MSE = 607$ ,  $p = .032$ ; gaze duration:  $F(1,26) = 5.62$ ,  $MSE = 1952$ ,  $p = .025$ ; in both cases, the interaction yielded  $F_s < 1$ ). For single-fixation duration, the effect of visual similarity did not reach significance,  $F(1,26) = 2.11$ ,  $MSE = 1281$ ,  $p = .158$ —note that, although admittedly ad hoc, we found an advantage of the visually similar condition over the visually dissimilar condition in the leading edge of the distribution (Cohen's  $d$  values: 0.67, 0.65, and 0.49 at the 0.1, 0.2, and 0.3 quantiles; the  $p$  values were 0.002, 0.004, and 0.017, respectively).

Finally, under the assumption that completion of at least an initial word identification stage (e.g., L1 in the E-Z Reader model) in the parafovea may induce readers to skip the word  $n + 1$ , we examined whether the probability of fixating the target word was higher when the preview was visually dissimilar than when the preview was visually similar. We found a higher probability of fixations on the target word when the preview was visually dissimilar than when the preview was visually similar (0.966 vs. 0.953,  $b = 0.35$ ,  $SE = 0.15$ ,  $t = 2.31$ ,  $p = .021$ ). In addition, the probability of fixations for the identity preview condition (0.947) did not differ from that of visually similar previews ( $b = -0.14$ ,  $SE = 0.139$ ,  $t = -1.03$ ,  $p > .30$ ).

## 4. Discussion

We designed a sentence reading experiment using Rayner's (1975) boundary change technique to examine the role of visual letter similarity—on the basis of visual similarity ratings—during the early moments of word identification while controlling for outline letter shape. To that end, the parafoveal preview on word  $n + 1$  could be a visually similar nonword preview (e.g., *frjto* for the target word *frito* [*fried*]; *i* and *j* are visually very similar [5.17 out of 7] in the Simpson et al., 2012, letter similarity norms) or a visually dissimilar nonword preview (e.g., *frgto*; *i* and *g* are visually different [1.53 out of 7]). For comparison purposes, an identity preview condition was also included. The eye fixation durations showed a reasonably consistent pattern: viewing times on target words were shorter when the parafoveal nonword preview was visually similar than when it was visually dissimilar, and this was accompanied by an advantage of the identity condition over the visually similar condition. These findings generalize the visual letter similarity effects reported by Marcet and Perea (2017) using masked priming to a reading scenario with parafoveal previews. Critically, the effects of visual letter similarity during parafoveal processing were not due to an uncontrolled influence of letter shape, as letter shape was the same for the visually similar and visually dissimilar conditions. In sum, visual letter similarity effects do occur in normal reading, hence generalizing the findings reported by Rayner et al. (1978, 1982) when manipulating outline letter shape. We must keep in mind that while outline letter shape per se may not influence word processing in normal skilled readers (see Paap et al., 1984; Perea & Panadero, 2014), letters that share the outline shape (e.g., *c/a* in *pcluce-palace*) tend to be more visually similar than those that do not share the outline shape (e.g., *y/a* in *pyltce-palace*).

One might argue that the effects of visual letter similarity in the initial stages of word processing (e.g., the processing advantage of the visually similar preview [*prime*] *dentjst* over the control *dentgst* for the target *dentist*; this Experiment; see also Marcet & Perea, 2017, 2018, for evidence with the masked priming technique) are at odds with the null



(caption on next page)

**Fig. 2.** Averaged viewing duration distributions across quantiles for first fixation durations (top), single fixation durations (middle), and gaze durations (bottom) in the visually similar and visually dissimilar parafoveal conditions. The Bars represent the Standard Errors.

effect of case alternation in the earliest stages of word processing (e.g., both *dentist* and *dEnTiSt* are equally effective at activating the target word *DENTIST*; Forster, 1998; Perea, Vergara-Martínez, & Gomez, 2015; see also Rayner et al., 1980, for eye movement evidence). However, these two phenomena reflect different processing levels. On the one hand, the effect of visual letter similarity originates when the featural visual information is mapped onto case-specific letter detectors. Because of perceptual noise in the visual system, the shape-specific letter detectors for the letter “i” may be activated when the stimulus contains a highly visually similar letter, such as the letter “j” in *dentjst*, which in turn would activate the complex case-insensitive letter detector of “i”. As a result, this explanation would correctly predict a processing advantage of *dentjst-dentist* over *dentgst-dentist*. On the other hand, the effect of case alternation does not originate early (i.e., the alternating-case prime *dEnTiSt* is as effective as the same-case prime *dentist*, Forster, 1998; see also Reingold, Yang, & Rayner, 2010, for evidence during sentence reading), but late in processing when the visual percept is compared with the stored representations in memory (see Perea et al., 2015, for discussion).

Further insights on the nature of the effects of visual letter similarity during reading can be obtained from distributional analyses on eye fixation durations. The rationale is the following: in evidence accumulation models (e.g., Ratcliff’s, 1978, diffusion model), a given effect may provide a head-start to word processing (i.e., faster encoding) or it may modulate the quality of information (i.e., decision processes). While in the first scenario, there would be just a shift in the response time or eye fixation duration distributions, the second scenario would also produce changes in shape—the slower condition would produce larger effects at the higher quantiles. As shown by Gomez, Perea, and Ratcliff (2013), masked repetition priming effects (identity vs. unrelated priming conditions) reflect shifts in the response time distributions. In contrast, lexical effects such as the word frequency effect (i.e., low vs. high frequency words) produce changes in both the location and shape of the response time distributions (greater word-frequency effects at the higher quantiles; see Gomez & Perea, 2014) or eye fixation durations (see Staub, White, Drieghe, Hollway, & Rayner, 2010). The present distributional analyses on eye fixation durations showed that the advantage of the visually similar condition over the visually dissimilar condition was approximately the same across quantiles, especially in first-fixation duration and gaze duration (i.e., a shift in the distributions; see Fig. 2). This pattern is consistent with the idea that the effects of visual letter similarity are due to an early “head-start” to word identification. That is, there is an initial encoding advantage of *frjto-frito* over the control *frgo-frito*, which is maintained during lexical processing (see Gomez et al., 2013, for modeling evidence of a shift in response time distributions in masked priming).

Taken together, the present findings show that, as predicted by Rayner et al. (1978), visual letter similarity modulates the integration of parafoveal and foveal information. Specifically, readers may benefit from the similarity between information extracted from the parafovea and the information extracted from the target once it is fixated in the fovea (i.e., a visually similar preview yields a benefit due to pre-activation of target letters). That is, when readers fixate on the target word *frito* (i.e., once the eye crossed the invisible boundary), there would be briefer viewing times when the parafoveal preview was a visually similar nonword (*frjto*) than when it was a visually dissimilar nonword (*frgto*). Additionally, visually similar previews may be more likely to be misidentified as the target word (e.g., see Gregg & Inhoff, 2016, for the role of misperceptions during reading). For instance, when readers are fixating the word “bien” in the sentence “Estaba todo bien frito en aceite de oliva” [“It was all well frjed in olive oil”], the letter j in the parafoveal preview *frjed* might be misperceived as the visually similar letter i, thus

explaining the higher skipping rate on that target word when the parafoveal preview was visually similar than when the parafoveal preview was visually dissimilar. A limitation of Rayner et al.’s (1978) preliminary letter identification hypothesis, however, is that it has not yet been implemented in a full model of eye movement control in reading.

How can contemporary models of eye movement control accommodate the present findings? The E-Z Reader model (Reichle et al., 1998; Reichle, Rayner, & Pollatsek, 2003) and the SWIFT model (Engbert et al., 2005) do not include a module for orthographic or lexical processing. Clearly, the specification of the initial mapping from visual objects to letter features and letter identity/position is a challenge for all models of visual word recognition and reading (see Rosa, Perea, & Enneson, 2016, for discussion). As Reichle (2015) pointed out, it is desirable that the models of eye movement control during reading are elaborated to provide a more complete account of the orthographic processes during word recognition and how they contribute to normal reading. This would require specifying how letter identity and letter position are initially attained and integrated from the parafoveal information. In this line, Bicknell and Levy (2010) proposed a rational model of eye movement control in reading that includes a detailed account on how readers acquire word information in a sentence. A key idea of the Bicknell and Levy (2010) proposal, which fits well with the preliminary letter hypothesis (Rayner et al., 1978), is that readers extract information from a noisy visual input in the spirit of the Bayesian reader model of visual word recognition (Norris, 2006; see also Norris & Kinoshita, 2012). The noisy input in the Bayesian reader model would produce some degree of uncertainty at the initial moments of processing with respect to both letter identities and letter identity, thus capturing not only the effects of visual letter similarity (e.g., *dentjst* would produce a similar perceptual inputs as *dentist*) but also the effects of transposed-letter similarity (e.g., *jugde* would produce a similar perceptual input as *judge*; see Johnson et al. (2007)). We acknowledge, however, that the size of these effects with the boundary change technique is small. For gaze duration, the difference between the visually similar condition and the visually different condition was 7 ms (284 vs. 291 ms, respectively); similarly, the magnitude of the transposed-letter similarity effect for internal letters reported by Johnson et al. (1997; Experiment 1) was 8 ms (300 ms for the transposed-letter condition; 308 ms for the replacement-letter condition). This suggests that readers can extract, on most occasions, accurate abstract orthographic representations from the parafoveal previews.<sup>3</sup> Indeed, the small size of visual letter similarity and transposed-letter effects with parafoveal previews is consistent with recent empirical evidence that shows that readers can extract semantic and high-level information from the parafoveal previews (see Hohenstein & Kliegl, 2014).

In sum, we examined the participants’ eye fixation durations in a sentence reading experiment with the boundary change technique using visually similar vs. visually dissimilar parafoveal previews on the basis of objective letter confusability, with letter shape controlled (e.g., *frjto* vs. *frgto* for the target word *frito*). Results showed shorter viewing times on the target word when the nonword preview was visually similar to the target word than when it was visually dissimilar. Further empirical and theoretical work is necessary to offer a comprehensive account of how visual letter similarity modulates the initial stages of word identification during sentence reading.

<sup>3</sup> For comparison purposes with the Marcet and Perea (2017) masked priming experiments, we focused on a relatively constrained set of highly visually similar letters. We acknowledge that further empirical research is necessary to examine the impact of visual letter similarity in the early stages of word processing during sentence reading for a larger set of visually similar letters (e.g., c/e, c/o) or multi-letter homographs (e.g., m/m; c/d).

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